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# A system dynamics approach in LCA to account for temporal effects—a consequential energy LCI of car body-in-whites

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**Abstract**
*Purpose* The purpose of this paper is to take steps towards a life cycle assessment that is able to account for changes over time in resource flows and environmental impacts. The majority of life cycle inventory (LCI) studies assume that computation parameters are constants or fixed functions of time. This assumption limits the opportunities to account for temporal effects because it precludes consideration of the dynamics of the product system.
*Methods* System dynamics methods are used in a consequential, fleet-based LCI that accounts for some aspects of the dynamics of the wider system. The LCI model compares the life-cycle energy consumption of car body-in-whites (BIWs) in Australia made from steel and aluminium. It incorporates two dynamic processes: the flow of BIWs into and out of the fleet, and the recycling of aluminium from end-of-life BIWs back into new BIW production. The dynamical model computes both product-based and fleet-based estimates.
*Results and discussion* The product-based computations suggest that an aluminium BIW consumes less energy than a steel BIW over a single life cycle. The fleet-based computations suggest that the energy benefits of aluminium BIWs do not begin to emerge for some time. The substitution of aluminium for steel is a low-leverage intervention that changes the values of a few parameters of the system. The system has a delayed, damped response to this intervention because the large stock of BIWs is a source of high inertia, and the long useful life leads to a slow decay of steel BIWs out of the fleet. The recycling of aluminium back into BIW production is a moderate-leverage intervention that initially strengthens a reinforcing feedback loop, driving a rapid accumulation of energy benefits. Dominance then shifts to a balancing loop, slowing the accumulation of energy benefits. Both interventions result in a measureable reduction in life-cycle energy consumption, but only temporarily divert the underlying growth trend.
*Conclusions* The results suggest that product-based LCIs overestimate the short-term energy benefits of aluminium by not accounting for the time required for the stock of preexisting steel components to decay out of the fleet, and underestimate the long-term energy benefits of aluminium components by not accounting for changes in the availability of recycled aluminium. The results also suggest that interventions such as lightweighting and other efficiency measures alone can slow the growth of energy consumption, but are probably inadequate to achieve sustainable energy consumption levels if the fleet is large.

**Keywords** Body-in-white · Car · Dynamical modelling · LCA · LCI · System dynamics

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## 1 Introduction

Lightweight cars and car components have been the subject of much investigation using the ISO 1404X life cycle assessment (LCA) technique (Standards Australia and Standards New Zealand 1998). In the majority of these studies, the life cycle inventory analysis (LCI) phase assumes that computation parameters are constants or fixed functions of time. This assumption serves to simplify the application of LCA, which is intentional in the design of

the technique, but also limits the opportunities to account for temporal and spatial effects. Consequently, most LCA models predominantly reflect the steady-state conditions (Klöpffer 2008). This limitation arises because the assumption precludes consideration of the dynamics of the product system. In this paper, the term ‘dynamics’ refers to the way that the state of a system changes over time in response to internally and externally generated forces. Since the LCA model does not account for the dynamics of the product system, it cannot estimate the product system’s behaviour over time. This paper examines the proposition that a reformulation of the LCA approach in terms of a system dynamics framework would help to overcome this limitation.

The specific aim of this paper is to take steps towards a LCA that is able to account for changes over time in resource flows and environmental impacts. This aim is achieved by (a) constructing a new LCI model using system dynamics methods and (b) comparing the LCI results obtained with the conventional and dynamical models. An example of a consequential (prospective or change-oriented) LCI is presented wherein the life-cycle energy consumption of a car component made of steel is compared with that of the same component made of aluminium. This LCI assumes an Australian context, using the system boundary and energy consumption data from Puri et al. (2009). It uses computation methods similar to Field et al. (2000) and Das (2000) and allows for growth in fleet size, similar to Das (2000). Unlike Field et al. (2000) and Das (2000), this LCI also allows for gradual adoption of the alternative product. The influence of the main assumptions is analysed with a sensitivity analysis. The management implications of the results of the dynamical computations are discussed in terms of Meadows’s (2009, pp. 145–165) leverage-point scale.

### 1.1 Literature review

The LCA studies on materials for car components can be divided into two categories: product-based (or product-centred) and fleet-based (or fleet-centred). *Product-based* LCA studies provide estimates of the life-cycle environmental impacts of a single product. These studies are particularly useful when comparing the impacts of either low-production-volume products or the product fleet at steady state. There are many product-based studies in the LCA literature. Most of the product-based studies assume that the model parameters, such as the proportion of recycled content in the product, are constants (e.g. Bertram et al. 2009; Buxman 1994; Carlsson 2009; Davies 2003; Dubreuil et al. 2010; Hakamada et al. 2007; Ribeiro et al. 2008; Tharumarajah and KoltunI 2007). A few of the studies account for temporal effects by assuming that some parameters change according to fixed functions of time. For example, Puri et al. (2009) assume that resource costs of energy and materials production generally increase with time, while Ungureanu et al. (2007) assume that the annual distance driven by a car decreases nonlinearly with its age.

The cited product-based LCA studies assume fixed computation parameters. This assumption is a simplification that precludes consideration of many of the interactions that occur between the elements of the product system, but interactions determine the system’s characteristic behaviour. A model that limits (or excludes) such interactions provides only a snapshot of the system’s behaviour. Therefore, the model may be accurate only over a short time period (or single point in time). Extrapolating the snapshot to cover a longer time period can be highly inaccurate if the system’s behaviour varies significantly with time. Allowance for interactions is also necessary in helping attempts to explain and explore the system’s response to management interventions, such as implementation of a new government policy. Ekvall et al. (2007) highlight similar limitations arising from the exclusion of dynamics in studies of waste management.

*Fleet-based* LCA studies provide estimates of the life-cycle environmental impacts of the product fleet, including the transient effects as new products replace end-of-life products in the fleet. These studies provide a more realistic estimate of the net impact of high-production-volume, multi-generation products. There are relatively few fleet-based studies in the LCA literature (e.g. Cáceres 2009; Das 2000, 2005; Field et al. 2000). The cited studies account for temporal effects by assuming that (a) the production rate of alternative products is constant, (b) the retiring rate of all products is a nonlinear function of either the fleet size or product age, and (c) the availability of recycled materials for the production of alternative products is a constant fraction of the number of end-of-life alternative products. Assumptions (b) and (c) make the LCI models dynamical. Comparisons between the baseline product and its alternative are made through either (1) an ab initio scenario, wherein two separate fleets, one using each product, are assumed to grow at the same rate up to a steady-state size, or (2) a displacement scenario, wherein a single fleet initially containing only the baseline product is gradually displaced by one containing the alternative product while maintaining a constant fleet size. Field et al. (2000) use a mathematical model and assumes that the retiring rate is either a classical exponential decay or a logistic decay (both of which are functions of fleet size). They present both ab initio and displacement scenarios and estimate carbon dioxide emissions. Cáceres (2009) builds on Field et al. (2000) by considering also the mass efficiency of material substitutions. Das (2000) uses a spreadsheet model and assumes that the retiring rate is a nonlinear function of product age. He presents an ab initio scenario and estimates both energy consumption and carbon dioxide emissions. Das (2005) uses a similar method as Das (2000) for a different product and estimates only energy consumption.

Both product-based and fleet-based studies generally show that the life-cycle environmental impacts of aluminium car components are lower than those of steel components, primarily due to the lower mass of aluminium components and the consequent lower fuel consumption and emissions during the use stage of the life cycle. Compared to product-based studies, fleet-based studies suggest that it takes longer for the higher energy investment in aluminium component production to be recovered through fuel savings during the use stage. Given that products such as cars and car components have long life cycles, and are produced in high volume, a fleet-based approach usually provides a more accurate model of the real situation.

### 1.2 System dynamics

The car component product system, with its long life cycles and wide boundaries, can respond in complex ways to management interventions. The emergent behaviour is often very different from the expected behaviour, and this discrepancy can result in frustration and misapplied effort on the part of managers and policy makers. Therefore, it is important to understand the possible responses of the whole system to potential management interventions, such as changes in the component itself, product demand, resource supply, and government policy.

The behaviour of a complex system is driven by two fundamental processes: accumulation and feedback. *Accumulation* is the process of filling and draining inventories or 'stocks' and operates at finite rates, thereby causing delayed system response to natural changes and human intervention. These delays are sources of inertia in complex systems and also introduce uncertainty into the design and implementation of management interventions (Sterman 2000). Car fleet size is an example of an accumulation. Changes in this stock are driven by the processes that add cars to the fleet and those that subtract cars from the fleet. *Feedback* is a pervasive and powerful cause-and-effect mechanism that operates when a change in an accumulation can feed back around a cause-and-effect loop to either amplify or resist the original change. The terms 'positive' or 'reinforcing' feedback are used to describe mechanisms that amplify change, and the terms 'negative' or 'balancing' feedback are used to describe mechanisms that resist change. For example, feedback effects drive episodic bursts of freeway construction—traffic congestion leads to pressure to build more freeways, the availability of new freeways leads to increased peri-urban development, increased development leads to more traffic, more congestion, more freeway construction, and so on around the loop (Sterman 2000).

The discipline of system dynamics provides a number of concepts and tools that are designed to enable the study of accumulation and feedback effects in complex systems. These effects can cause a product system to behave in a complex manner greatly different from that expected on the basis of static or linear mental models (Ashford 2001; Forrester 1995). Thus, a system dynamics approach can estimate a product system's environmental impact more accurately than an approach that assumes fixed computation parameters.

System dynamics models help to explore possible futures and support the development of 'what if' scenarios. Scenarios of relevance to the present study include (a) the impact of replacing steel components with aluminium components and (b) the potential impact of legislation requiring car manufacturers to recover, recycle, and reuse the materials in their end-of-life cars. System dynamics models are particularly useful in consequential LCA studies, which aim to estimate the future environmental impacts of changes to existing products (Sandén and Karlström 2007). They can also aid in assessments of the likelihood of the success of a product change and help to identify sources of uncertainty so that robust solutions can be sought.

## 2 Methods

The present study builds on existing LCA and LCI studies by constructing and applying a consequential, fleet-based LCI that accounts for some aspects of the dynamics of the wider system. It is an LCI study that uses a system dynamics approach to compare the life-cycle energy consumption associated with car components in Australia made from steel and aluminium. There is considerable interest and research into the use of aluminium and other lightweight materials to replace steel in car components, with the primary goal being to reduce the fuel consumption of cars.

The scope of the present LCI study is similar to that of the cited research. The *product* is the body-in-white (BIW), the load-carrying welded frame to which other moving components are attached. The product system includes the technical, energy-consuming processes that enable the BIW to be produced, used, and recycled at end-of-life. The *system boundary* is the same as that used by Puri et al. (2009), an Australian LCA study that compares the life-cycle environmental impact of car door skins made from either steel, aluminium, or a composite material. The only resource flow considered is energy flow. The two material options considered are steel and aluminium.

Within the wider system, many variables influence energy consumption, and energy consumption, in turn, influences many variables. The latter span the realms of economy (e.g. resource costs, manufacturing investment), environment (e.g. resource availability, pollutant emissions), and society (e.g. customer preferences, probability of road accidents). Udo de

Haes et al. (2004) note that an attempt to consider the dynamical effects of all processes of the life cycle makes the modelling task too complex and the data requirements too extensive. Instead, they suggest either modelling a small number of core processes or applying dynamical modelling and LCA separately as part of a toolbox approach.

The present LCI study is an example of the first approach of modelling a small number of core processes. The model incorporates two dynamic processes which are based on the same three assumptions as the cited fleet-based studies. The first process involves the flow of BIWs into and out of the fleet. The model assumes that the production rate of aluminium BIWs increases linearly from zero at time zero, reaching full adoption in 20 years, and that the retiring rate of all BIWs can be represented by an exponential decay of fleet size, assuming the decay rates used by Field et al. (2000). The second process is the recycling of aluminium from end-of-life BIWs back into new BIW production. The model assumes that the availability of recycled materials for the production of aluminium BIWs is a constant fraction of the number of end-of-life aluminium BIWs. In reality, these two processes contain a number of critical lifetimes, of which the model incorporates only one—the time BIWs spend in the fleet. The average useful life of cars in Australia is assumed to be 19 years (based on Australian Automotive Intelligence 2010, pp 28, 44). Other system delays are measured in months and are not modelled because they have a minor influence on the results—these delays include the time between BIW production and use, and the time between BIW retirement and new BIW production from the same aluminium.

The hypothesis concerning the main interactions embodied in these two dynamic processes is represented in the *causal loop diagram* of Fig. 1 (the feedback loops are shown in bold). The dynamical hypothesis involves three main assumptions regarding the behaviour of manufacturers and recyclers. First, aluminium BIWs are a new technology, meaning that all preexisting BIWs are made from steel and aluminium BIWs will phase into production over time. Second, in producing BIWs, manufacturers will exhaust their own supply of recycled aluminium before using external sources of aluminium. Third, all of the aluminium recovered from end-of-life BIWs are used to make more BIWs. The second and third assumptions are impractical because manufacturers do not recycle their own cars, but the net result of these assumptions is relatively accurate. Demand for recycled aluminium is higher than its supply despite its lower purity than virgin aluminium. Therefore, recycled aluminium from an end-of-life BIW will probably substitute for virgin aluminium in another product, still resulting in a reduction in energy consumption.

The hypothesis illustrated in Fig. 1 assumes that there is a reinforcing loop and a balancing loop acting simultaneously. In both loops, any increase in production of recycled or virgin aluminium BIWs will lead to more aluminium BIWs reaching end-of-life, which will increase availability of recycled aluminium. An increase in avail-

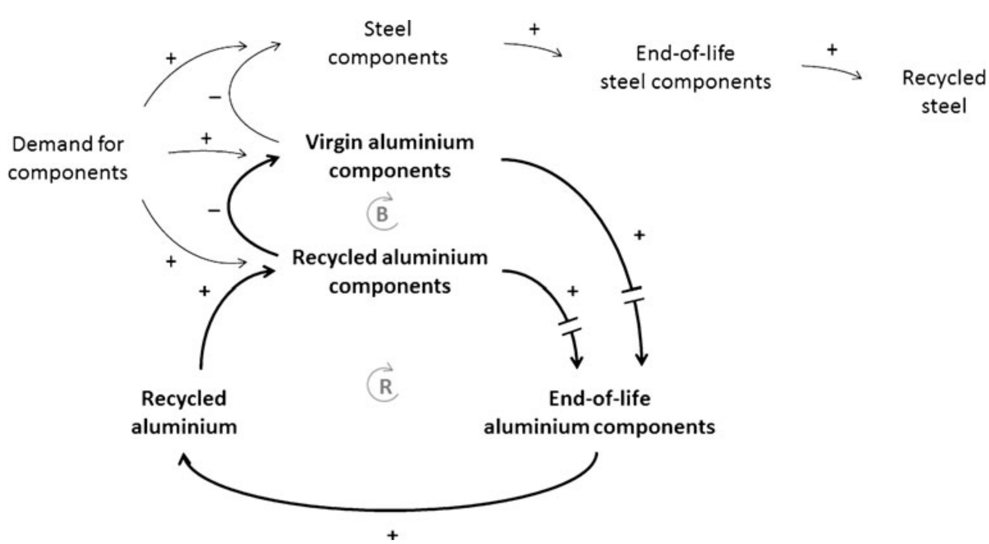


**Fig. 1** A causal loop diagram representing the hypothetical recycling system. The *text elements* represent system state variables, and the *arrows* represent influence links. The *plus* (+) and *minus* (−) *signs on the arrows* indicate link polarity. A *plus sign* indicates that an increase/decrease in the value of the variable at the *tail of the arrow* will cause the value of the variable at the *head of the arrow* to increase/decrease above/below what it otherwise would have been (all else being equal). A *minus sign* indicates that an increase/decrease in the value of the variable at the *tail of the arrow* will cause the value of the variable at the *head of the arrow* to decrease/increase below/above what it otherwise would have been (all else being equal). The *double slash* (//) *sign* indicates a *significant delay* between a change in the value at the *tail of the arrow*, the corresponding change in the value at the *head of the arrow*. The *encircled R* indicates a *reinforcing feedback loop*, and the *encircled B* indicates a *balancing feedback loop*

ability of recycled aluminium leads to an increase in the production of recycled aluminium BIWs in the reinforcing loop and a decrease in the production of virgin aluminium BIWs in the balancing loop. Together, these two loops have the effect of nonlinearly increasing the proportion of recycled aluminium BIWs and decreasing the proportion of virgin aluminium BIWs.

In order to perform the required LCI computations, a low-order *stock-and-flow model* was constructed using the modelling software STELLA™ (version 9.1.2). The structural arrangement of this model is summarised in Fig. 2 (the dominant feedback loops are shown in bold). The feedback loop can be enabled by setting 0<'Recovery'≤1 or disabled by setting 'Recovery'=0.

The present LCI considers the displacement scenario, wherein a single fleet initially containing only steel BIWs is gradually displaced by aluminium BIWs. Table 1 shows the parameter values used in the computations. The mass of steel BIWs is 430 kg (Lovins and Cramer 2004). The mass of aluminium BIWs is 300 kg, estimated by scaling the mass of the steel BIW (Kelkar et al. 2001). Steel BIWs and the external sources of steel are assumed to contain 25% recycled content (Das 2000, 2005; Ungureanu et al. 2007). The initial batch of aluminium BIWs and the external sources of aluminium are assumed to contain 10% recycled content. This value is low because the quality of recycled aluminium is not currently suitable for the wrought aluminium components that comprise most of a BIW (Carle and Blount 1999; Cáceres 2009), but the quality is assumed to increase with the adoption of aluminium BIWs. The initial size of the fleet is 12 million BIWs, the size of the Australian car fleet in 2010 (Australian Bureau of Statistics 2011). Unlike the cited fleet-based studies, which assume a steady-state fleet size, the present LCI study assumes that the demand for cars ('Demand for components' in Fig. 2) will vary in proportion to the population size. The Australian population is projected to continue to grow over the next 100 years, with the growth rate gradually decreasing (Australian Bureau of Statistics 2008). The demand for cars is assumed to also grow from 894,000 BIWs/year to 1.89 million BIWs/year. When the recycling loop is disabled, 'Recovery' is 0%; when the recycling loop is enabled, 'Recovery' is assumed to be 90%, which accounts for both losses of end-of-life BIWs and losses of the aluminium in those BIWs (Field et al. 2000; Ungureanu et al. 2007). The energy consumption data and useful life data were adapted from Puri et al. (2009).

## 3 Results

Figure 3 shows the life-cycle energy consumptions computed, using the stock-and-flow model of Fig. 2 and the parameter

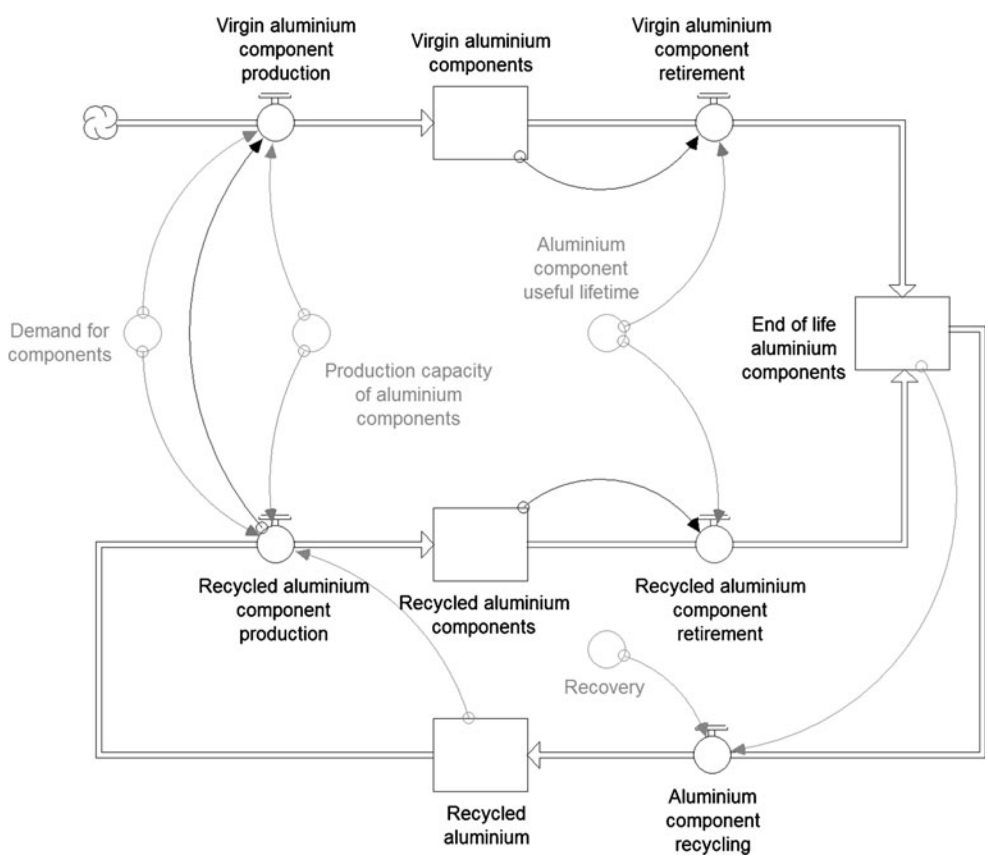


**Fig. 2** A stock-and-flow model representing the hypothesised recycling feedback and delay structures, and the associated variables. The *boxes* represent *stocks* (e.g. 'Recycled aluminium components'), the *double-lined arrows* represent *flows* (e.g. 'Recycled aluminium component production'), the '*tap' symbols* represent *flow rates* (e.g. rate of 'Recycled aluminium component production'), the *single-lined arrows* represent *influence links* (e.g. the stock of 'Recycled Aluminium' influences the rate of 'Recycled aluminium component production') and the '*cloud' symbols* represent *unlimited sources and sinks* outside the system boundary. Each variable contains either a value or a mathematical formula

**Table 1** Parameter values used for computations of the life-cycle energy consumption

| Parameter | Units | Steel | Aluminium |
|---|---|---|---|
| BIW | | | |
| Mass | kg | 430 | 300 |
| Recycled content | % | 25 | 10, 10+ |
| Fleet size, initial | BIWs | 12 million | |
| Production rate | | | |
| Initial | % of production capacity | 100 | 0 |
| Growth rate | % of production capacity/y | −5 | 5 |
| Demand for cars | | | |
| Initial | BIWs/year | 894,000 | |
| Final | BIWs/year | 1,890,000,000 | |
| Useful life | | | |
| Time | years | 19 | |
| Distance | km | 300,000 | |
| Recovery | % | n/a | 0, 90 |
| Energy consumption, production | | | |
| Virgin | MJ/kg | 35.2 | 190.1 |
| Recycled | MJ/kg | 19.0 | 57.1 |
| Energy consumption, use | MJ/kg/year | 37.1 | 36.1 |

values listed in Table 1. The computations were made over a period of 100 years. The assumed growth in 'Demand for components' produces growth in the car fleet from 12 million cars to 33 million cars over 100 years.

The 'product-based steel' curve shows the energy consumption of an all-steel BIW fleet. This quantity is the algebraic product of the energy consumption of a single BIW and fleet size. The 'product-based aluminium' curve, computed similarly, shows the energy consumption of an all-aluminium BIW fleet containing 10% recycled content. As is the case in the cited product-based studies, these two results suggest that an aluminium BIW consumes less energy than a steel BIW over a single life cycle; in this computation, 17% less energy.

The 'fleet-based decay' curve shows the energy consumption of the fleet under the displacement scenario with the

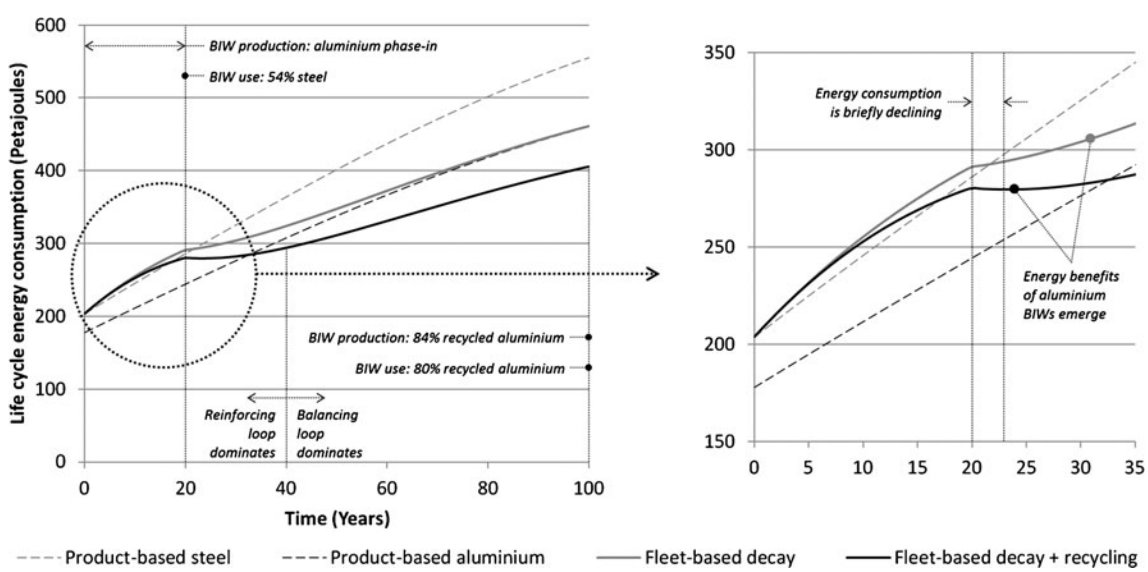


**Fig. 3** Comparison of total life-cycle energy consumption of steel and aluminium car components as determined by the product-based LCI model and the fleet-based LCI model. The *horizontal axis* represents the time period over which the computations were made, with initial conditions at time zero approximating the real conditions in Australia in the year 2010. The *vertical axis* represents the life-cycle energy consumption of the product fleet, computed every 0.1 years using the Runge–Kutta 4 integration method. The *encircled portion of the diagram* is magnified in the *right-hand panel*

recycling feedback loop *disabled*. This curve diverges nonlinearly from the 'product-based steel' curve at time zero and converges with the 'product-based aluminium' curve at about year 100. At year 20, when aluminium BIW production is fully phased-in, steel BIWs still constitute 54% of the fleet. This result is due to the long delay between BIWs entering and leaving the fleet. The 'fleet-based decay' curve in the subgraph of Fig. 3 shows that the energy benefits of aluminium BIWs do not begin to emerge until year 31. That is, 31 years is required for the higher energy investment in aluminium component production to be recovered through fuel savings during the use stage. Field et al. (2000) and Cáceres (2009) call this period of time the 'crossover time'; Das (2000) and Das (2005) call it the 'life-cycle equivalence'.

The 'fleet-based decay + recycling' curve shows the energy consumption of the fleet under the displacement scenario with the recycling feedback loop *enabled*. This curve is similar to the 'fleet-based decay' curve, but diverges nonlinearly until it is 12% lower at year 100. At this point, 84% of aluminium BIWs are being produced from recycled content, and 80% of aluminium BIWs in use are made from recycled content. The two curves diverge because a greater proportion of aluminium BIWs can be made from recycled aluminium, which is assumed to require about three times less energy to produce than virgin aluminium. The 'fleet-based decay + recycling' curve in the subgraph of Fig. 3 shows that the energy benefits of aluminium BIWs do not begin to emerge until year 24.

The four main assumptions of the model are (a) the duration and pattern of the adoption period for aluminium BIWs, (b) the growth in demand for components, (c) the average useful life of the aluminium BIWs, and (d) the recovery of aluminium from end-of-life BIWs. Table 2 shows the results of a sensitivity analysis, which takes the 'fleet-based decay + recycling' curve as the base case, on these assumptions. Variation in the main assumptions can advance or delay the energy benefits by up to 5 years, except when assuming 40-year, S-shaped adoption of aluminium BIWs. In this case, the energy benefits are delayed by 12 years because most of the growth in demand for components occurs between year 15 and year 30.

## 4 Discussion

The similarities and differences between the curves in Fig. 3 lead us to four conclusions: First, the fleet-based curves are similar to the 'product-based steel' curve over the first 20 years, despite full phase-in of aluminium BIW production. The management intervention involved—the substitution of aluminium for steel—simply changes the values of a few parameters of the system. This type of management intervention (i.e. changing the numbers) is the most commonly applied but usually has low leverage for change (Meadows 2009, p148). The system has a delayed, damped response to the management intervention because the stock of BIWs in use is 13 to 19 times greater than the flow of BIWs produced and retired each year and also because the average useful life of BIWs is relatively long. The large stock is a source of high inertia, and the long useful life leads to a slow decay of steel BIWs out of the fleet.

Second, the two fleet-based curves have similar shapes and values. This management intervention involved—the recycling of aluminium back into BIW production—initially strengthens the reinforcing feedback loop against the limiting effect of the balancing loop. The reinforcing loop dominates over the first 40 years and drives a relatively rapid divergence of the curves between years 20 and 40. After this period, dominance shifts to the balancing loop because there is an upper limit to the proportion of

**Table 2** Results of the sensitivity analysis on the four main assumptions of the model

| Parameter | Value | Time for energy benefits | Reduction in life-cycle energy consumption | |
|---|---|---|---|---|
| | | | Year 50 (PJ) | Year 100 (PJ) |
| Base case | | 24 years | 1,600 | 7,800 |
| Adoption | 40 years | 25 years | 930 | 6,800 |
| | S-shaped | 26 years | 1,500 | 7,700 |
| | 40 years, S-shaped | 36 years | 690 | 6,600 |
| Demand for components | 100% to 80% | 21 years | 2,100 | 11,000 |
| | 100% to 120% | 27 years | 1,100 | 4,300 |
| Useful life | 14 years | 19 years | 2,900 | 13,000 |
| | 24 years | 28 years | 670 | 3,100 |
| Recovery | 100% | 23 years | 1,700 | 8,200 |
| | 50% | 27 years | 1,200 | 6,400 |

*PJ* petajoules

BIWs that can be made of recycled content. The balancing loop slows the transition from virgin BIW production to recycled BIW production. This type of management intervention (i.e. changing feedback loop dominance) usually has moderate leverage for change (Meadows 2009, pp155–156). The system's response to the management intervention is to drift nonlinearly to a new energy consumption level that is lower than the original level.

Third, both management interventions result in a measureable reduction in life-cycle energy consumption, but only temporarily divert the underlying growth trend. Energy consumption begins declining very slightly in year 20, but then resumes growing in year 23 because growth in 'Demand for components' becomes the dominant driver again. This result suggests that management interventions such as lightweighting and other efficiency measures alone can slow the growth of energy consumption, but are probably inadequate to achieve sustainable energy consumption levels if the fleet is large. A reduction in energy consumption to a sustainable rate is more likely to be achieved by seeking higher-level leverage points, such as changing the rules or goals of the system, or changing the paradigm on which the system is built (Meadows 2009, pp158–165). One such management intervention is a move away from car-centric cities towards people-centric urban development. The benefits of this shift, which include a reduction in energy consumption and an increase in wealth, have already been estimated by Kenworthy et al. (2005) in a comparison of 84 cities around the world.

Finally, the fleet-based curves extend beyond the bounds set by the product-based curves. This result highlights the limitation of assuming fixed computation parameters, particularly the proportion of recycled content in aluminium BIWs. As this proportion increases with time, the lower bound set by the 'product-based aluminium' curve shifts down. This shift, and in particular the rate at which it occurs, is not seen with the product-based computations.

The use of a system dynamics approach results in a minor increase in complexity of application. It is likely, however, that any attempt to acquire a more complete result will require additional investment, as is the case in the cited fleet-based studies. Compared with the product-based LCI, the fleet-based LCI requires additional knowledge—in particular, an understanding of how to apply system dynamics concepts and tools. The inclusion of additional feedback loops that involve elements beyond the car and its components will require even more data and a deeper understanding of the product system.

System dynamics helps to understand how changes in certain elements of the product system influence both other elements and the product system as a whole. This information is valuable for system redesign—be it the introduction of a new technology, a new management approach, or a policy intervention—to the extent that it enables management interventions that can be strategically applied to known points of high leverage. The key is to move the leverage points in the right direction. Forrester (cited in Meadows 2009, p145) suggests that although leverage points can often be identified intuitively, designed management interventions usually and unintentionally push the lever in the wrong direction because the intervener's mental model does not accurately take account of the dynamics of the system.

A system dynamics approach helps to provide a more complete estimate, but is always limited by the modeller's limited understanding of the real product system, and the model's simplifications and assumptions. It is more important to understand the influence of key dynamics on the variables of the model than to attempt to compute the absolute values of the variables. In this sense, the relative shapes of the curves in Fig. 3 are more important than the values on the axes.

The energy benefits of aluminium BIWs are estimated to emerge at the later end of the range estimated by the cited fleet-based studies (7–31 years). The main reasons for this result are that the present computation assumes growth in demand for cars and a longer average useful life of BIWs. The energy benefits, over 100 years, can be increased by decreasing the demand for components (changing the feedback loop) or decreasing the average useful life of aluminium BIWs (changing the numbers). Decreasing the demand requires the manufacture of fewer cars, which decreases material consumption. Decreasing the useful life requires more frequent replacement of cars, which increases material consumption and economic costs. The demand for components has higher leverage than the average useful life of aluminium BIWs (Meadows 2009).

## 5 Conclusions

This paper presented a fleet-based LCI wherein a system dynamics approach was used to compare the life-cycle energy consumption of steel BIWs with that of aluminium BIWs. The results showed that a system dynamics approach is a potentially useful way to account for temporal effects in LCI computations. A single dynamical model can be used to compute both product-based and fleet-based estimates, and it can include key interactions of the real product system, leading to more realistic results. The fleet-based LCI example of substituting aluminium BIWs for steel BIWs suggests that product-based LCIs (a) overestimate the short-term energy benefits of aluminium by not accounting for the time required for the stock of preexisting steel components to decay out of the fleet and (b) underestimate the long-term energy benefits of aluminium components by not accounting for changes in the availability of recycled aluminium.

The inherent uncertainty in consequential LCA studies can be quite large since the assumptions made are numerous and may be projected over a long time period. A system dynamics approach is justified when its results differ significantly from the results of an approach that assumes fixed computation parameters. This difference in results will be significant if the management interventions considered can be applied to leverage points that are high on the Meadows scale.

It is suggested that additional research be undertaken to further explore the dynamics of the product system, to explore the response of the product system to other management interventions, to compute the life-cycle material consumption, and to conduct dynamical LCI studies for other material options.

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## References

Ashford AC (2001) Unexpected behaviors in higher-order positive feedback loops. MIT, USA. http://sysdyn.clexchange.org/sdep/Roadmaps/RM7/D-4455-2.pdf. Accessed 24 Sept 2009

Australian Automotive Intelligence (2010) Australian Automotive Intelligence Yearbook 2010, 9th edn. Australian Automotive Intelligence, Melbourne

Australian Bureau of Statistics (2008) 3222.0–Population projections, Australia, 2006 to 2101. Commonwealth of Australia, Canberra

Australian Bureau of Statistics (2011) 9390.0–Motor vehicle census. Commonwealth of Australia, Canberra

Bertram M, Buxmann K, Furrer P (2009) Analysis of greenhouse gas emissions related to aluminium transport applications. Int J Life Cycle Assess 14(Suppl 1):S62–S69

Buxman K (1994) Ecological aspects of the use of aluminium in cars, with particular regard to recycling techniques. Resour Conserv Recycl 10(1–2):17–23

Cáceres CH (2009) Transient environmental effects of light alloy substitutions in transport vehicles. Mater Des 30(8):2813–2822

Carle D, Blount G (1999) The suitability of aluminium as an alternative material for car bodies. Mater Des 20(5):267–272

Carlsson BT (2009) Selecting material for the exterior panel of a private car back door by adopting a total cost accounting approach. Mater Des 30(3):826–832

Das S (2000) The life-cycle impacts of aluminum body-in-white automotive material. J Miner Met Mater Soc 52(8):41–44

Das S (2005) Life cycle energy impacts of automotive liftgate inner. Resour Conserv Recycl 43(4):375–390

Davies G (2003) Materials for automobile bodies. Butterworth-Heinemann, Oxford, pp 224–228

Dubreuil A, Bushi L, Das S, Tharumarajah A, Xianzheng G (2010) A comparative life cycle assessment of magnesium front end autoparts. SAE 2010 World Congress & Exhibition, April 2010, Detroit, MI, USA, Session: Sustainable Manufacturing, Materials and Components

Ekvall T, Assefa G, Björklund A, Eriksson O, Finnveden G (2007) What life-cycle assessment does and does not do in assessments of waste management. Waste Manag 27(8):989–996

Field F, Kirchain R, Clark J (2000) Life cycle assessment and temporal distributions of emissions: developing a fleet-based analysis. J Ind Ecol 4(2):71–91

Forrester JW (1995) Counterintuitive behavior of social systems. Technol Rev 73(3):52–68

Hakamada M, Furuta T, Chino Y, Chen Y, Kusuda H, Mabuchi M (2007) Life cycle inventory study on magnesium alloy substitution in vehicles. Energy 32(8):1352–1360

Kelkar A, Roth R, Clark J (2001) Automobile bodies: can aluminum be an economical alternative to steel? J Miner, Met Mater Soc 53 (8):28–32

Kenworthy J, Murray-Leach R, Townsend C (2005) Sustainable urban transport. In: Hargroves K, Smith M (eds) The natural advantage of nations: business opportunities, innovation and governance in the 21st century. Earthscan, London

Klöpffer W (2008) Life cycle sustainability assessment of products. Int J of Life Cycle Assess 13(2):89–95

Lovins AB, Cramer DR (2004) Hypercars, hydrogen, and the automotive transition. Int J Veh Des 35(1/2):50–85

Meadows DH (2009) Thinking in systems: a primer. Earthscan, London

Puri P, Compston P, Pantano V (2009) Life cycle assessment of Australian automotive door skins. Int J Life Cycle Assess 14(5):420–428

Ribeiro I, Peças P, Silva A, Henriques E (2008) Life cycle engineering methodology applied to material selection, a fender case study. J Clean Prod 16(17):1887–1899

Sandén BA, Karlström M (2007) Positive and negative feedback in consequential life-cycle assessment. J Clean Prod 15(15):1469–1481

Standards Australia and Standards New Zealand (1998) Australian/New Zealand Standard: Environmental management–Life cycle assessment–Principles and framework, AS/NZS ISO 14040:1998. Standards Australia, Sydney, and Standards New Zealand, Wellington

Sterman JD (2000) Business dynamics: systems thinking and modeling for a complex world. McGraw-Hill, Boston

Tharumarajah A, KoltunI P (2007) Is there an environmental advantage of using magnesium components for light-weighting cars? J Clean Prod 15(11–12):1007–1013

Udo de Haes HA, Heijungs R, Suh S, Huppes G (2004) Three strategies to overcome the limitations of life-cycle assessment. J Ind Ecol 8(3):19–32

Ungureanu CA, Das S, Jawahir IS (2007) Life-cycle cost analysis: aluminum versus steel in passenger cars. In: Das SK, Yin W (eds) Aluminium alloys for transportation packaging aerospace and other applications. TMS, USA